Evidence for a change in the nuclear mass surface with the discovery of the most neutron-rich nuclei with $17 \leq Z \leq 25$

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The results of measurements of the production of neutron-rich nuclei by the fragmentation of a ^{76}Ge beam are presented. The cross sections were measured for a large range of nuclei including fifteen new isotopes that are the most neutron-rich nuclides of the elements chlorine to manganese (^{50}Cl, ^{53}Ar, ^{55,56}K, ^{57,58}Ca, ^{59,60,61}Sc, ^{62,63}Ti, ^{65,66}V, ^{68}Cr, ^{70}Mn). The enhanced cross sections of several new nuclei relative to a simple thermal evaporation framework, previously shown to describe similar production cross sections, indicates that nuclei in the region around ^{62}Ti might be more stable than predicted by current mass models and could be an indication of a new island of inversion similar to that centered on ^{31}Na.

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Exploration of new isotopes with excess neutrons has yielded many surprises in nuclear physics. Weak binding of valence neutrons was found to result in an extended matter distribution or halo [1]. The textbook shell structure of nuclei was found to evolve, primarily due to the importance of a tensor force in nuclei, unlike atomic shell structure [2]. One of the earliest indications of significant changes in the structure of nuclei with excess neutrons was the discovery of enhanced nuclear binding of heavy sodium isotopes [3]. This is now understood as a result of the significant contributions of intruder orbitals to the ground-state configuration of these isotopes [4, 5]. The region of nuclei near ^{31}Na where the neutron fp-shell contributes significantly to the ground-state structure is now known as the "island of inversion."

One of the challenges of nuclear physics is to push the study of neutron-rich isotopes to higher atomic number and an important benchmark in this work is to find the maximum number of neutrons that can be bound for each atomic number. Often the delineation of the heavy limit of stability, called the neutron drip-line, itself has yielded surprises. Recently it was found that heavy isotopes of aluminum are likely more bound than predicted [6]. Continuing this work, we report here the next step towards the fundamental goal of defining the absolute mass limit for chemical elements in the region of calcium.

The neutron drip line is only confirmed at present up to $Z = 8$ (^{24}O$_{16}$) through years of work at projectile fragmentation facilities in France [7, 8], the US [9] and Japan [10]. The neutron drip line has been found to rapidly shift to higher neutron numbers at $Z = 9$, i.e., ^{31}F$_{22}$ has been observed several times [11, 12, 13]. The nuclide ^{30}F$_{21}$ has been shown not to exist and ^{32}F$_{23}$ is thought to be unbound based on systematics while the particle stability of ^{33}F$_{24}$ is an open question. The shift is predicted to continue at higher masses [14, 15, 16] and makes the search for the neutron drip line in this region even more challenging. The fragmentation of ^{48}Ca$_{28}$ projectiles at RIKEN in Japan [11], at GANIL in France [12], and at the NSCL in the US [6, 13, 17] has produced a number of heavier nuclei in this region including ^{40}Mg$_{28}$ and ^{42}Al$_{29}$, but no clear limit has been established yet. On the other hand, all nuclei up to $Z = 12$ with $A = 3Z + 3$ have been shown to be unbound. The fragmentation of heavier stable beams such as ^{76}Ge in which ^{52}Ar was observed [18] is necessary in order to go beyond the reported work.

In the present work a primary beam of ^{76}Ge was fragmented and a search for new neutron-rich isotopes above ^{40}Mg was carried out using the recently developed tandem fragment separator technique [6]. It was previously shown by Tarasov et al. [17] that the cross sections for projectile fragments in this region have an exponential dependance on Q_g (the difference in mass-excess of the beam particle and the observed fragment that is independent of the target in contrast to the older Q_{gg} four-body analysis applied to low energy reactions) and deviations from the predicted yield may be used to identify anomalies in the mass surface such as the new island of inversion near ^{62}Ti predicted by Brown [19] similar to the original island of inversion near ^{31}Na.

A 132 MeV/u ^{76}Ge beam from the Coupled Cyclotron Facility at the National Superconducting Cyclotron Laboratory was used to irradiate a series of ^{9}Be targets (see below) and finally a tungsten target located at the target position of the A1900 fragment separator [20]. The primary beam current was monitored continuously and

normalized to Faraday cup readings during the course of the experiment. The average beam intensity for the measurements of the most exotic fragments was 32 pnA. The A1900 fragment separator was combined with the S800 analysis beam line to form a two-stage separator system as described in Ref. [6]. A two-stage separator provides a high degree of rejection of unwanted reaction products and allows the identification of each fragment of interest. During the search for the most exotic fragments, a Kapton wedge (20.2 mg/cm^2) was used at the center of the A1900 to reject less exotic fragments at the A1900 focal plane by an 8 mm aperture. The transmitted fragments passed on to the S800 beam line for event-by-event momentum analysis and particle identification. The momentum acceptance of the A1900 was set to $\Delta p/p = \pm 0.05\%$, $\pm 0.5\%$, $\pm 1\%$ and $\pm 2.5\%$ as the production rate of the increasingly exotic nuclei decreased, always with an angular acceptance of 8.2 msr.

The particles of interest were stopped in a stack of eight silicon PIN diodes (50×50 mm^2) with a total thickness of 8.0 mm that provided multiple measurements of the energy-loss and thus made redundant determinations of the nuclear charge of each fragment along with the total kinetic energy. The time of flight (TOF) of each
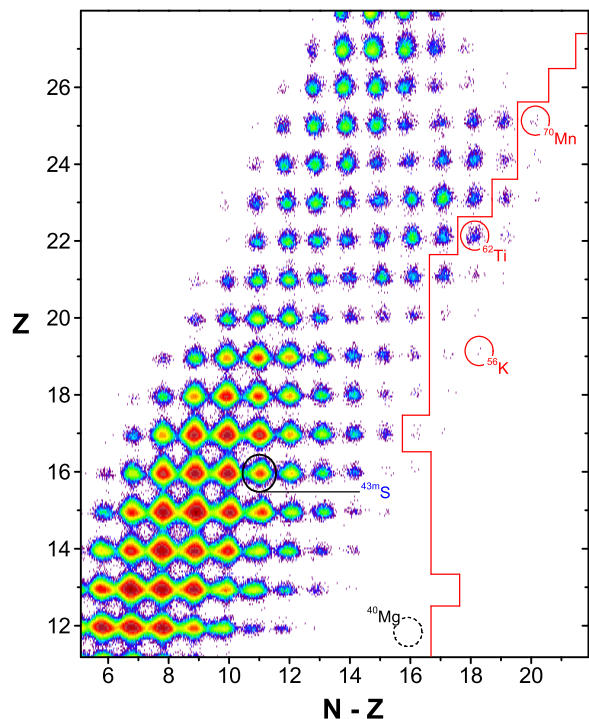

FIG. 1: (Color online) Particle identification plot of the measured atomic number, Z, versus the calculated function $N-Z$ for the nuclei observed in this work, see the text for details. The limit of previously observed nuclei is shown by the solid line as well as the positions of several reference nuclei.

particle that reached the detector stack was measured in four ways: (1) over the 46.04 m flight path between a thin plastic scintillator located at A1900 focal plane and the second PIN detector, (2) over the 20.97 m flight path between another thin plastic scintillator at the object point of the S800 analysis beam line and the third PIN detector, (3) over the entire 81.51 m flight path by measuring the arrival time relative to the phase of the cyclotron rf-signal and the third PIN detector, and (4) over the 25.07 m path between the scintillators at the object point and the A1900 focal plane. The magnetic rigidity of each particle ($B\rho$), which is proportional to the momentum/charge, was obtained by combining a position measurement in two parallel-plate avalanche counters (PPAC's) at the dispersive plane of the S800 analysis line with NMR measurements of the dipole fields. The simultaneous measurement of multiple ΔE signals, the magnetic rigidity, the total energy, and the TOF's of each particle provided an unambiguous identification of the atomic number, charge state and mass number of each isotope. The position in a PPAC in front of the silicon detectors allowed additional discrimination against various scattered particles. The detection system and particle identification was calibrated with the primary beam and by the locations of gaps corresponding to unbound nuclei in the particle identification spectrum.

The approach of changing the target thickness while maintaining the magnetic system at essentially constant magnetic rigidities was used in order to simplify the particle identification during the run while mapping the (parallel) momentum distributions of the less exotic fragmentation products. The details will be described in a subsequent report [21]. Beryllium targets of thicknesses 9.8, 97.5, 145, 191, 288, 404, and finally 629 mg/cm^2 were inserted sequentially over the course of the experiment. The particle identification depended critically on the magnetic rigidity of the S800 analysis line and thus was constant during the experiment whereas the average energy (and rigidity) of a given reaction product decreased dramatically with increasing target thickness. Thus, the isotopic selection of this system moved towards heavier fragments with increasing target thickness. The magnetic rigidities were $B\rho = 4.355$ Tm (after the target), 4.334 Tm (after the wedge), 4.320 Tm (after the first TOF scintillator) and 4.305 Tm (after the second TOF scintillator) for the 629 mg/cm^2 target when the most exotic nuclei were observed. The power of this approach can be seen in Fig. 1 that shows the distribution of fully-stripped reaction products observed during this work. The range of fragments is shown as the measured atomic number, Z, versus the function $N-Z$ where N is the calculated neutron number. The absolute identification of the individual isotopes in Fig. 1 was confirmed by the identification of gamma rays from isomeric states in ^{32}Al and ^{43}S with a high-purity germanium detector placed near the silicon detector stack.
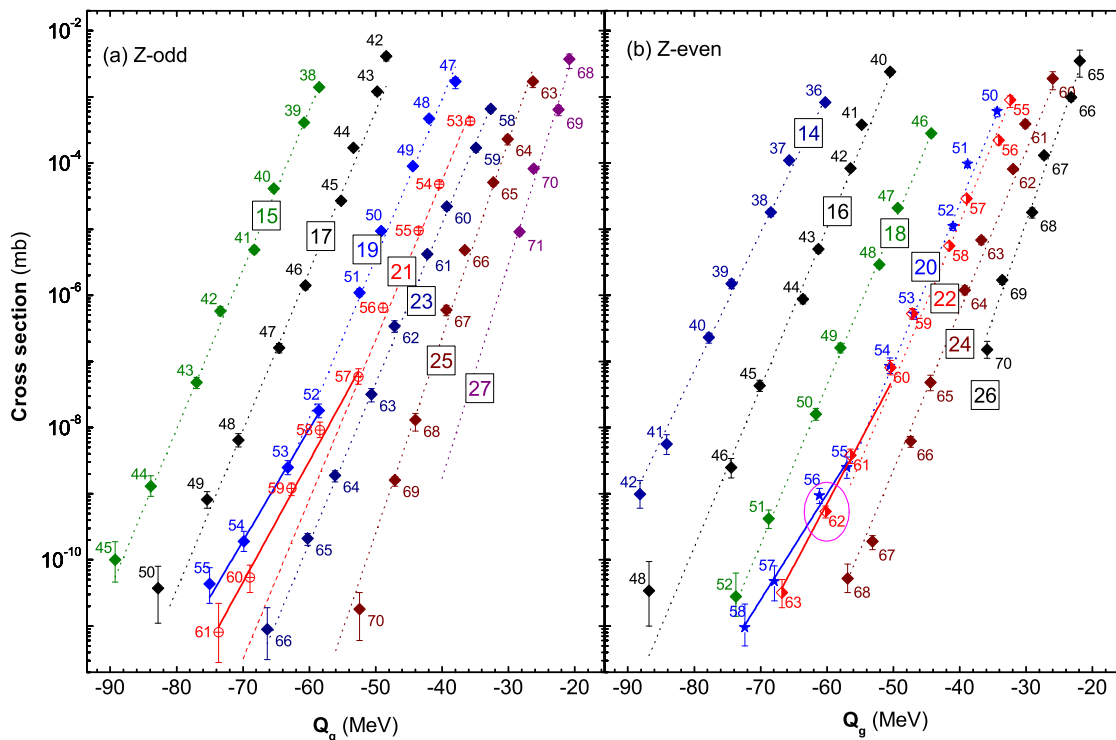
FIG. 2: (Color online) The cross sections for production of neutron-rich nuclei with (a) odd atomic numbers and (b) even atomic numbers with a Be target in the present work. See text for explanation of the lines. The cross section for ^{62}Ti at the center of the proposed new island of inversion [19] is circled.

A search for the most exotic nuclei was carried out by performing several runs with the 404 and 629 mg/cm^2 Be targets for a total of 50.83 hours and additional runs with a 567 mg/cm^2 ^{nat}W target with various stripper foils for a total of 77.66 hours. In contrast to previous studies, i.e. [9, 17], the present efficiency was dominated by the acceptance of the tandem separator and not by the data acquisition system due to the high selectivity of the separator system. The angular and total transmissions were calculated for each isotope for each run using a model of the momentum distribution with parameters obtained from the measured parallel momentum distributions. For example, the angular and total transmissions for ^{66}V with the 404 mg/cm^2 target were $99.0^{+0.7}_{-1.6}\%$ and $58\pm4\%$, respectively. The typical uncertainty in the total transmission for other cases was $\approx 5\%$.

The observed fragments include fifteen new isotopes that are the most neutron-rich nuclides of the elements chlorine to manganese (^{50}Cl, ^{53}Ar, ^{55,56}K, ^{57,58}Ca, ^{59,60,61}Sc, ^{62,63}Ti, ^{65,66}V, ^{68}Cr, ^{70}Mn). The new neutron-rich nuclei observed in this work are those events to the right of the solid line in Fig. 1 and are indicated by the

red squares in Fig. 3. We should note that the observation of ^{51}Cl was reported some time ago among the products from the reaction of ^{48}Ca $+^{64}$Ni at the relatively low energy of 44 MeV/u [22]. While not conclusive, the previous identification of this isotope may have been masked by the presence of the hydrogen-like ion ^{48}Cl^{16+} produced at the same time.

The cross sections for the production of all of the nuclei observed with the beryllium targets are shown in Figs. 2 (a) and (b) for product nuclei with odd and even atomic numbers, respectively. No nuclear reaction model can reproduce the very low yields of the exotic nuclei observed in this study and thus we will consider the general behavior of the production cross sections. Projectile fragmentation processes are usually described as a sudden process that forms an excited prefragment followed by statistical decay. Charity [23] has pointed out that the sequential evaporation of light particles from sufficiently excited nuclei follows a general pattern that leads to a somewhat uniform distribution of final products. Such uniform distributions underlay the EPAX systematics [24] that is often used to predict the yields of fragmentation reactions when designing experiments. We have recently shown
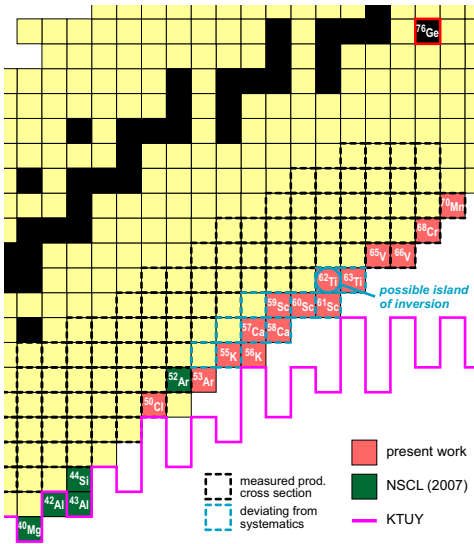
FIG. 3: (Color online) The region of the chart of nuclides under investigation. The solid line is the limit of bound nuclei from the KTUY mass model [16]. Nuclei in the green squares were recently discovered [6, 17, 18], those in red squares are new in this work, and the cross sections for those in dashed boxes are shown in Fig. 2. The center of the new proposed island of inversion at ^{62}Ti [19] is highlighted.

[17] that the yields of neutron-rich projectile fragments generally show a smooth exponential decline with the function:

$$Q_g = ME(Z_p, A_p) - ME(Z, A)$$

where $ME(Z, A)$ is the mass excess of a product with atomic number, Z, and mass number, A, $Z_p = 32$ and $A_p = 76$. The Q_g function depends on the relative binding energies of the projectile fragments without regard to the target nucleus and is a plausible basis for comparison of products from a process that creates a set of highly excited intermediate nuclei that then statistically populate the mass surface.

Figure 2 shows that the Q_g function using masses from from Ref. [16] (a representative calculation selected from among many others that give similar results) provides an excellent systematization of the new data with the logarithm of the cross sections for each isotopic chain falling on an approximately straight line. The isotopic chains with $15 \leq Z \leq 24$ can be fit with a single exponential slope of $1/1.8 MeV$, as shown by the dashed lines. However, closer inspection shows that the heaviest members of the isotopic chains with Z=19, 20, 21 and 22 break away from the uniform fit and the heaviest four or five isotopes have a shallower slope or enhanced cross sections. Recall that the masses of these most neutron-rich nuclei are not fit in the model but are extrapolated. This might indicate that these nuclei are more bound (i.e., less negative Q_g) than current mass models predict. One reason for a stronger binding can be deformation. In a

shell-model framework, the wave functions of the ground and low-lying excited states of nuclei in the new island of inversion around ^{62}Ti would be dominated by neutron particle-hole intruder excitations across the $N = 40$ sub-shell gap, leading to deformation and shape coexistence.

In summary, fifteen new neutron-rich isotopes were observed by fragmentation of a ^{76}Ge beam provided evidence for The general decline of the cross sections for the production of all of the observed neutron-rich isotopes with increasing mass number is consistent with the well-known EPAX parameterization and with the recently established Q_g systematics. The new data show a smooth exponential dependence with the mass excess of the observed fragment with a few exceptions. The fact that the cross sections of the most neutron-rich nuclei with $Z = 19$ to 22 are enhanced relative to the lighter isotopes may indicate that these nuclei and their precursors are more bound than predicted and is reminiscent of the discovery of the island of inversion at $N = 20$.

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